

# Cryogenic Analysis Tool Applied to Lunar Architectures

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**[Abstract] Storing cryogenic propellants for lunar missions possesses great potential for mass savings over the course of the mission. The Cryogenic Analysis Tool is an analytical model that returns information critical to deciding on the storage scheme for liquid hydrogen, methane, and oxygen fuels. The tool's current uses in determining which fuel storage system offers the greatest mass savings, newly implemented procedures and functionality, and future applications are discussed herein.**

## Nomenclature

<i>CAT</i>	=	Cryogenic Analysis Tool
<i>GUI</i>	=	Graphical User Interface
<i>LH<sub>2</sub></i>	=	Liquid Hydrogen Cryogenic Propellant
<i>LCH<sub>4</sub></i>	=	Liquid Methane Cryogenic Propellant
<i>LOX</i>	=	Liquid Oxygen Cryogenic Propellant
<i>MLI</i>	=	Multilayer Insulation
<i>UDF</i>	=	User Defined Function
<i>VBA</i>	=	Visual Basic for Applications

## I. Introduction

C RYOGENIC propellants are common fuels employed in the exploration of space. These include either LH<sub>2</sub> or LCH<sub>4</sub> along with their oxidizer, LOX. In order to minimize the required volume for storing these chemicals, they are tanked at saturated liquid temperatures in insulated steel or aluminum tanks as liquids. Even though the temperature of deep space is estimated to be around 4K, Earth albedo and infrared heating raise the environmental temperature of typical low-Earth Orbit locations to approximately 237K.<sup>1</sup> This temperature is comparatively hot to the cryogenic fluid temperatures of LH<sub>2</sub> (23K), LOX (90K), and LCH<sub>4</sub> (130K) and causes these liquids to vaporize inside the tanks. The resulting vapor pressure must be vented to space in order to preserve the structural integrity of the propellant tanks. This lost propellant mass is referred to as boil-off, the principle concern in cryogenic fluid storage. Minimizing the launch mass of the fuel and storage systems requires analytical evaluation using an application such as CAT to compare several strategies of cryogenic fuel storage: passive and active thermal control systems. The use of CAT to determine which thermal protection scheme to employ is of greatest use for long duration missions especially those requiring significant time spent in orbit or on the surface of the earth, Moon, or Mars.

## II. Thermal Protection Systems

CAT compares the individual component masses of the two more common thermal protection system designs used in space exploration: passive and active thermal control. Both of these systems deal with the problems associated with propellant loss to boil-off in different manners, and a discussion of their analysis, design, and application follows.

### A. Thermal Tank Modeling

Storage tank heating rates directly correlate to the amount of fuel vented as boil-off. Primary heat sources that contribute to boil-off include tank surface heating, heat conducted to the tank wall through penetrations, tank support structure conduction, and mixer heating. Heat absorbed through the surface area of the tank and mixer

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heating is readily modeled and well documented, however the specific effects of penetrations on overall tank heating rates are considerably less well defined.<sup>2</sup>

Fill lines, vent lines, tank pressurization lines, and support struts are all connected to the tank body through the tank insulation. These penetrations act as heat sources to the tank at their interface. They absorb heat all along their length which is then conducted to both ends, one of which is the tank wall. Penetration heating is a function of their overall length and the geometry/area of the tank wall interface. As more penetrations are connected to a given storage vessel, the overall tank heating rate increases significantly.

Support structure such as common bulkheads, rings, and struts contribute significantly to heating rates as well. CAT currently allows for a selection among seven different support schemes in order to approximate their heating contributions to the design.

## B. Passive Thermal Control

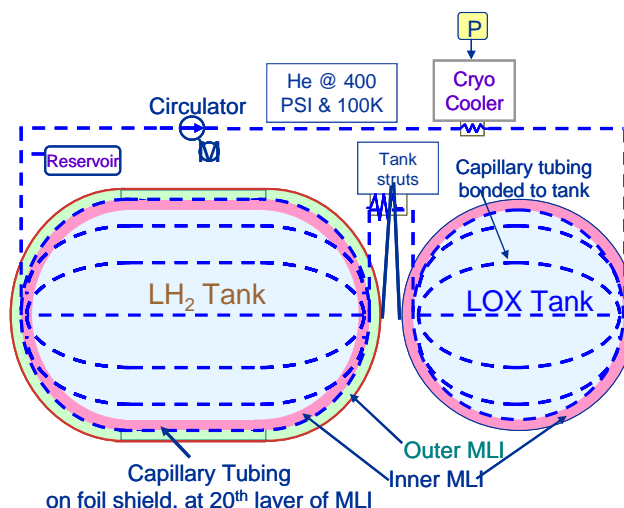
Passive thermal control consists of a four step iterative process: insulating the tank against radiative heat transfer, analytically assessing the amount of boil-off that will occur during a mission, over sizing the tank and insulation system to compensate for the boil-off, and predicting the boil-off for the re-dimensioned storage vessel.

The insulation system can consist of any combination of the following components, spray on foam insulation (SOFI), multilayer insulation (MLI), and typically flexible optical solar reflectors (FOSR). Spray on foam insulation covers the steel shell of the tank in a layer typically several centimeters thick. SOFI is the only insulation on the Space Shuttle's external tank and acts as the first measure of insulation. MLI consists of numerous layers of alternating double aluminized mylar radiation foils and silk netting. Typically between 40 and 60 layers of MLI are employed on a tank. MLI provides significant thermal protection in space since the primary mode of heat transfer is radiation. The silk netting spaces out the mylar sheets to minimize conduction between the foils, and the foils are effective at radiating environmental heat back to space, minimizing that which enters the tank. FOSR's attempt to reduce the heat absorbed by the system by reflecting as much radiation as possible away from the craft and acts as a tough and robust outermost layer of protection.

After inputting the insulation system design into CAT, a predicted boil-off is returned. The tank must then be dimensioned to include the volume of propellant vented as boil-off so that the mission critical fuel mass is maintained. However, this increased tank volume augments the surface area of the storage vessel which increases the amount of boil-off predicted. CAT applies an iterative scheme to return a final tank dimension, boil-off estimation, and individual component masses.

## C. Active Thermal Control

A more complex system of compensating for cryogenic fuel boil-off is considered for long duration missions. Active thermal control employs cryocoolers and gaseous helium circulation to remove heat from the storage tanks and either reduce or completely eliminate boil-off. This system consists of the following components: cryocooler, heat exchanger, radiator, structural integration, helium reservoir tank, circulator compressor, tubing, circulator compressor solar array, and the cryocooler solar array. All of the component masses and sizes are returned as outputs from CAT when applied to an active thermal control system. Active cooling also uses an insulation system just like passive cooling (SOFI, MLI, FOSR) but the helium cooling tubes are located in between two layers of the MLI typically at 40% of the total MLI thickness.<sup>1</sup> When applied to LOX storage tanks, the active control system is sized to maintain zero boil-off performance, however because of current cryocooler limitations and in the interest of mass and

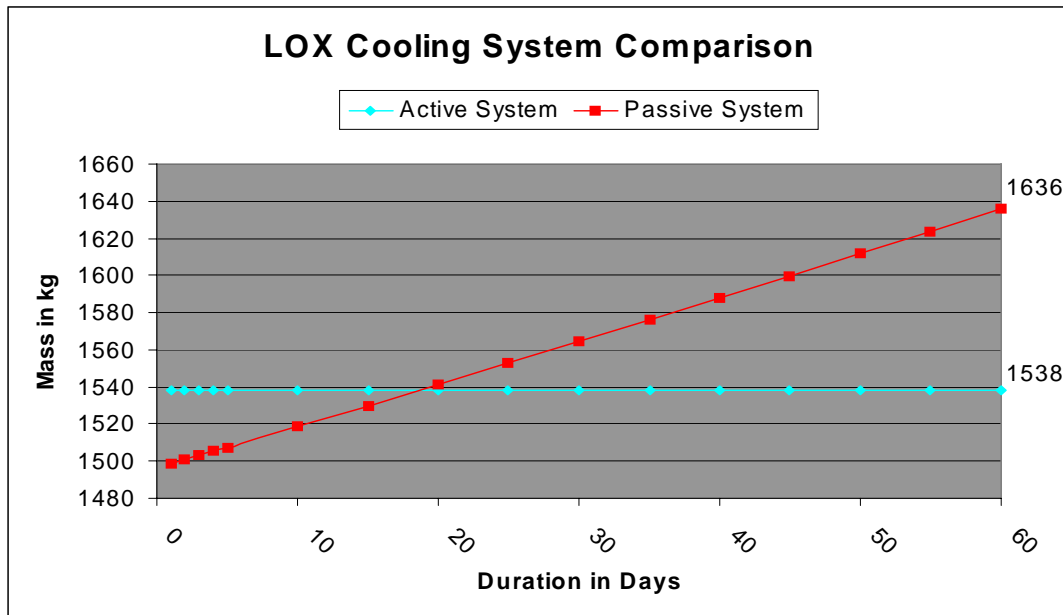


**Figure 1. Active Thermal Control. Representative diagram of active cooling design for zero boil-off LOX cooling and reduced boil-off LH<sub>2</sub> cooling.<sup>1</sup>**

costs, the best case scenario for LH<sub>2</sub> storage is a reduced boil-off scenario. LH<sub>2</sub> fuel's boiling point falls well below what can be achieved by practical cryocoolers, so our approach taken is to couple the cooling of the LH<sub>2</sub> tank with the LOX tank (maintained at zero boil-off conditions) in series and cooled to around 100K. A visual representation of this system appears in Fig. 1.

#### D. Assessing Mass Savings

CAT returns component masses and individual heat calculations for all components of either the passive or active thermal control designs. The outputs can be used as a baseline to aid in producing the final storage design. Comparing active and passive thermal control designs by total system mass for a particular mission type presents important information on assessing which system should be employed. Often, the passive system is selected even when mass savings is present with an active case because of the complexity and high costs that are associated with the active cooling design unless the difference is significant.



**Figure 2.** Total mass comparison for active and passive thermal control systems. Representative mission at 300K, 1.5m spherical tank diameter, SOFI, 50 layers of MLI, FOSR present. Graph and data generated by newly implemented parametric analysis routines.

Figure 2 shows the total mass of each system at a constant temperature for increasing orbital durations. The two system masses are equivalent at day 18 for the parameters used in this calculation. The active system requires a greater launch vehicle lift-off of mass because of all the additional components besides the tank and insulation system, however for LOX storage the mass does not increase with storage duration since its boiling point is within readily achievable cryocooler temperatures. The passive scheme mass increases because of the greater boil-off associated with longer durations. The passive thermal control mass is a function of boil-off, tank growth, and insulation growth masses. For LH<sub>2</sub> storage, the active system mass would increase at a significantly lesser rate than that of the passive concept because of the reduced boil-off scheme employed.

### III. CAT Additional Functionality

My contributions to CAT consist of moderate spreadsheet revision with the greatest modifications made via VBA macros, functions, and routines. Several of the developments are used every time a calculation with the tool is made while many others are used on an as-needed basis to study key parametrics of the design

My largest contribution to the CAT lies in the enhanced ability to perform parametric analysis of both the passive and active systems. Prior to the writing of these parametric codes, CAT performed overall system analysis point design by entering the mission parameters, changing a variable, and then repeating this dozens of times by manually inputting the changing parameters. The new parametric applications run autonomously in less than ten seconds and return all significant component masses to a new sheet so that they can be readily referenced and

graphed. Parametric variables include layers of MLI, tank diameter, mission duration, and environmental temperature. All these analyses but one can be performed for both active and passive control systems for LH<sub>2</sub>, LCH<sub>4</sub>, and LOX storage tanks. Parametric analysis of temperature for active thermal control was not deemed necessary for development at this time.

#### **A. Improved Automated Calculation**

Old macro codes used in CAT were worked on by several different programmers at various times and consisted of their adaptations of Excel recorded macros. Recorded macros operate extremely inefficiently since they take into account a great number of possible actions while they are being formed in order to perform (typically) one task. Their methods of cell referencing are also indirect and slow down all but the fastest computers significantly during operation. I rewrote the existing macros using direct cell referencing and faster calculation schemes as well as including detailed comments in order to describe the code to other future programmers. These changes increase the usability, reliability, and ease of modification for current and future users.

#### **B. Thermal Conductivity Double Interpolation**

In order to increase the accuracy of conductive heat transfer calculations through tank penetrations and storage vessels, I conducted a literature examination to compile a thermal conductivity database now included in CAT. This datasheet was created in a format conducive to automated search and double interpolation for a range of temperatures. I then programmed a double interpolation lookup function that operates behind the scenes in the "Penetrations" sheet in order to return an accurate thermal conductivity value for a particular material at a designated average temperature. This routine operates whenever a cell is changed within a specified range on the "Penetrations" sheet and can readily be adapted to additional materials in the database by adding the data in the same format as the existing properties.

#### **C. Tank Segment Heat Function**

Existing in older version of the CAT spreadsheets are representations of the Lockheed Equation which is used to calculate heat transfer through MLI in space. The equation calculates the heat in three parts, radiation between layers, gaseous conduction as a function of interstitial pressure, and conduction through the silk netting separating each mylar sheet<sup>3</sup>. The equation contains only three terms but its length renders it difficult to understand in Excel spreadsheets. I removed the equation into a VBA module and rewrote it as a user defined function. The UDF takes in several arguments from the spreadsheet and calculates the MLI heat via the Lockheed Equation in a step by step process allowing for easier modification and comprehension. The module contains several paragraphs justifying the thought process behind the code and was written as efficiently as possible. The new function automatically updates the cell contents rapidly so as not to hinder the use of other macros, and calculates the exact values determined by the original equations. The code for this function can be viewed in the Appendix.

#### **D. Mission Input Store/Recall Routine**

CAT's versatility allows its application to a variety of missions with specific tank sizes, geometries, penetration dimensions, mission segments at varying temperatures, and insulation systems. In order to save this data, previously the entire workbook was saved to the hard drive. The file occupies more than 10 MBs, wasting storage space and time when multiply files are loaded in their entirety for comparison. I created a save/load procedure through VBA that allows the user to specify a mission name and save or load the mission parameters to a new worksheet at the end of the file. It also saves important heating parameters as a calculation summary so that recalculation can be avoided. This usability allows for greater ease of comparison between missions as well as implementing an automated archiving and retrieving process at the click of a button.

### E. Scale Image Generation

When comparing thermal loads on cryogenic fluids due to penetration heating rates, line sizes and geometries are often assumed for the calculations. The assumed dimensions for feed/vent, drain, and pressurization lines may often be completely inadequate for the volume of tank used for the thermal analysis. I designed a routine which would allow the CAT user to automatically generate a graphical representation of a tank and insulation system with penetrations, all drawn to scale. The insulation system can be composed of any combination of SOFI, MLI, and FOSR that is selected for the mission. The scale image generation allows the user to determine at a glance, whether or not the assumed line sizes are appropriate for the specified tank. The routine also allows for the optional inclusion of representative struts and the display of heat rates through the fill/vent line, drain line, pressurization line, struts, and MLI. It will also display other information about the tank dimensions. The user's input is taken from their mission specifications as well as through the use of a Graphical User Interface (GUI) displayed in Figure 3.

## IV. Conclusion

The Cryogenic Analysis Tool now has increased capabilities in parametric analyses, code efficiency and readability, speed of calculation, generated image line size inspection, material properties and thermal conductivity database, and mission parameter storage and recall. These preparations further ready the CAT for its distribution as a standardized cryogenic storage design tool.

### A. Further Study

Future modifications to the CAT include more detailed tank penetration heating calculations and the creation of a database of penetration and tank dimensions to reference for heat scaling. When an effective LH<sub>2</sub> temperature cryocooler is developed, its shield design needs to be implemented into the CAT's calculations as an additional fuel storage option. Mass calculations and radiative heat reduction for an integrated shade of various geometries should be further developed and eventually included as an option in the insulation systems for all three cryogenic fluid tanks. The most important modifications are those that will come after the CAT is validated against experimental data on heating and boil-off rates in LEO. This would most likely be modeled in vacuum chambers able to simulate the LEO environment, and after data is collected and analyzed this point of reference would be used to modify the CAT's calculations in order to more accurately represent actual implementation of design schemes.

## Appendix

```
*****
'* This program was created by Adam Pfendt in July of 2007 while on internship with the NASA
'* Academy in conjunction with NASA Glenn Research Center and at the request of Dave Plachta.*
*****
Option Explicit
```

```
Public Function MLISegHeat(Propellant As String, MissionSeg As Integer, Zone As String, _
    TEnv As Double)
```

```
'This function will calculate the heat load on a particular environmental temperature zone
```

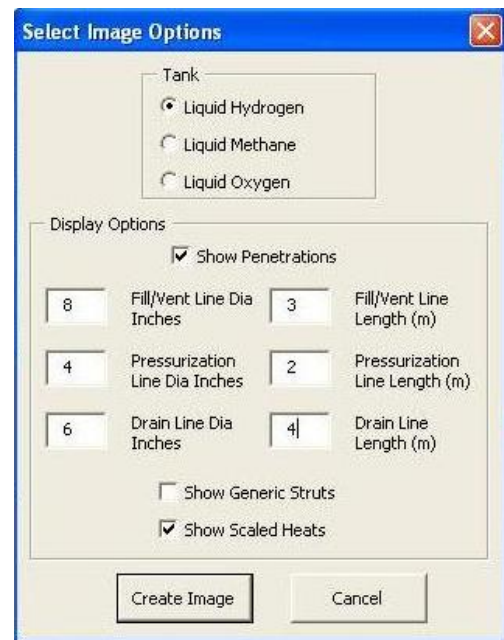


Figure 3. Image Generation GUI.

' Propellant can be entered by typing "Hydrogen", "Methane", or "Oxygen" including the quotes.  
 'or by selecting a cell with the name already in it.  
 ' MissionSeg is the segment of the mission that heat is being calculated for so that the cell  
 'references can adjust accordingly.  
 ' Zone needs to be entered with quotes as "T1", "T2",... or "T6" and is used to adjust cell  
 'references  
 ' TEnv is the cell that contains the temperature for that appropriate zone. If this argument is  
 'removed from the code, then some other way must be found for the function to auto-update itself  
 'whenever a change is made to the sheet. it was originally done with application.volatile but  
 'this was extremely slow and slows all the parametric macros

'defines variables to be used in heat calculation, variables are abbreviations for:

Dim SATank, SASeg, TsatL, Layers, AvgDens As Double  
 Dim CondCoef, RadCoef, GasCoef, Expon, Emiss, PInter As Double  
 Dim CondTerm, RadTerm, PInterTerm As Double

'defines variables used to change the cell references for the above variables

Dim ColOffset, RowOffset, MLIRowOffset, Cyl As Integer

\*\*\*\*\*OFFSET VARIABLES\*\*\*\*\*

'The following section reads in the user's arguments from the function and will increment the  
 'offset variables so that the cell references are appropriately modified depending on the user's  
 'input.

' ColOffset is 0,1, or 2 and represents the column for the particular fuel selected. A  
 'value of 0 refers to hydrogen, 1 column to the right is methane, and 2 columns is oxygen.  
 ' RowOffset is either 0 for hydrogen and methane or 3 for LOX. This value is necessary because  
 'the LOX environmental temperatures are located 3 rows lower than those for the other two.  
 ' MLIRowOffset has a value of 3 for hydrogen or 0 for either LOX or LCH<sub>4</sub>. This increment is  
 'needed because the LH<sub>2</sub> MLI data is 3 rows lower than the data for the other propellants.  
 ' Cyl is a value of 1 or 2. It is 1 when the heat is being determined for either end cap, and  
 'since the surface area used from the CAT sheets is total end cap surface area, when multiplied  
 'by .5 and this value it comes out to be the surface area of one cap. Consequently, for the  
 'cylindrical section, Cyl=2 and 2\*.5=1 so the entire cylindrical surface area is used.

```
If UCase(Propellant) = "HYDROGEN" Then
  ColOffset = 0
  RowOffset = 0
  MLIRowOffset = 3
Else
  If UCase(Propellant) = "METHANE" Then
    ColOffset = 1
    RowOffset = 0
    MLIRowOffset = 0
  Else
    If UCase(Propellant) = "OXYGEN" Then
      ColOffset = 2
      RowOffset = 3
      MLIRowOffset = 0
    Else
      MLISegHeat = "Error! Arguments(Propellant, Mission Segment, 'Zone')"
    End If
  End If
End If
```

End If

If UCase(Zone) = "T1" Or UCase(Zone) = "T4" Then

**'first end cap heat calculations**

    Cyl = 1

Else

    If UCase(Zone) = "T2" Or UCase(Zone) = "T5" Then

**'cylinder heat calculations**

        Cyl = 2

    Else

        If UCase(Zone) = "T3" Or UCase(Zone) = "T6" Then

**'second end cap heat calculations**

            Cyl = 1

        Else

            MLISegHeat = "Error! Arguments(Propellant, Mission Segment, 'Zone')"

        End If

    End If

End If

\*\*\*\*\***READ IN VARIABLES**\*\*\*\*\*

**'stores the value for each variable from its appropriate location in the workbook to be used in**

**'the heat calculations of the 3rd section**

**'Tank Surface Area**

    SATank = Sheets("Passive").Range("E33").Offset(0, ColOffSet).Value

**'Segment Surface Area: can be either end caps or cylinder**

    SASeg = Sheets("Passive").Range("E32").Offset(1 - Cyl, ColOffSet).Value

**'Temperature of Saturated Liquid**

    TsatL = Sheets("Passive").Range("E14").Offset(0, ColOffSet).Value

**'Number of Layers of MLI**

    Layers = Sheets("MLI Props").Range("T9").Offset(MLIRowOffSet, 0).Value

**'Average Density of MLI**

    AvgDens = Sheets("MLI Props").Range("U9").Offset(MLIRowOffSet, 0).Value

**'Conduction Coefficient**

    CondCoef = Sheets("MLI Props").Range("F7").Offset(MLIRowOffSet, 0).Value

**'Radiation Coefficient**

    RadCoef = Sheets("MLI Props").Range("G7").Offset(MLIRowOffSet, 0).Value

**'Gas Conduction Coefficient**

    GasCoef = Sheets("MLI Props").Range("H7").Offset(MLIRowOffSet, 0).Value

**'Exponent**

    Expon = Sheets("MLI Props").Range("I7").Offset(MLIRowOffSet, 0).Value

**'Intralayer Emissivity**

    Emiss = Sheets("MLI Props").Range("D7").Offset(MLIRowOffSet, 0).Value

**'Interstitial Pressure (torr)**

    PInter = Sheets("MLI Props").Range("E7").Offset(MLIRowOffSet, 0).Value

\*\*\*\*\***HEAT CALCULATIONS**\*\*\*\*\*

**'This section of the code calculates the segment heat from conduction, radiation, and gaseous**

**'conduction. It then multiplies these values by another term which includes segment/tank**

**'surface area ratio, and MLI layers before adding them together.**

### **‘Lockheed Equation<sup>3</sup>**

$\text{CondTerm} = (\text{CondCoef} * \text{AvgDens} ^ 2.56) / \text{Layers} * (\text{TEnv} ^ 2 - \text{TsatL} ^ 2) / 2$

$\text{RadTerm} = \text{RadCoef} * \text{Emiss} / \text{Layers} * (\text{TEnv} ^ 4.67 - \text{TsatL} ^ 4.67)$

$\text{PInterTerm} = \text{GasCoef} * \text{PInter} / \text{Layers} * (\text{TEnv} ^ \text{Expon} - \text{TsatL} ^ \text{Expon})$

$\text{MLISegHeat} = (\text{Cyl} * 0.5 * \text{SASeg} / \text{SATank}) * (\text{Layers} / (90 - 45) * (1.17 - 1) + 0.83) * \_$   
 $(\text{CondTerm} + \text{RadTerm} + \text{PInterTerm})$

End Function

### **Acknowledgments**

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### **References**

<sup>1</sup> Plachta, D. W., Christie, R. J., Carlberg, E., and Feller, J. R., “Cryogenic Propellant Storage Analyses and Design Tool Evolved from In-Space Cryogenic Propellant Depot Project,” C3-N-01, 2007.

<sup>2</sup> Plachta, D. W., and Kittle, P., “An Updated Zero Boil-Off Cryogenic Propellant Storage Analysis Applied to Upper Stages or Depots in an LEO Environment,” NASA TM-211691, 2003.

<sup>3</sup> Johnson, W.R., “Thermal Performance of Multilayer Insulations,” NASA CR-134477, 1974.